



Fracture Mechanics Tool Development
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Advanced Finite Element Modeling Of Low Cycle Fatigue Crack Growth

WARP3D

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Overview

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- Fracture Control Process
- Examples of Need
- Technical Approach Details
- Participants and Roles



The Fracture Control Process

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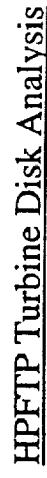
Overview

- Assumes a crack-like defect of a size which may be missed in inspection will exist in most critical location of any critical structure or component.
- Flaw existence assumption is usually, but not always, conservative based on past experiences in NASA and knowledge of manufacturing processes.
- Cyclic, environmental, and sustained loads used to generate stresses on models.
- Fracture Mechanics analysis used to predict crack growth and residual strength.
- Must show that defective structure will still provide four times required mission lifetime.
- Special exemptions cover redundant structures, low risk parts, etc.
- Assessments require specialized software tools, experienced analysts, and reliable material crack growth rate test database.



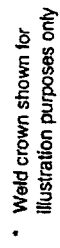
- ◆ High stresses and regions of localized yielding combined with the hydrogen environment result in extremely small critical initial flaw sizes predicted by LEFM analysis

- ◆ Requires extraordinary NDE to meet fracture control - very costly
- ◆ Considerable expense and effort to produce even the limited LEFM analysis





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- Technical drawing of a large throat piece weld identification. The drawing shows a side view of a mechanical assembly. Key components and labels include:
- Weld 12 Inset**: A circular inset at the bottom right showing a detailed view of a weld joint.
 - Large Throat Piece Weld Identification**: The main title of the drawing.
 - Outlet Elbow**: A curved pipe component at the top left.
 - Inlet Elbow**: A curved pipe component at the top right.
 - Overlays**: A label pointing to a circular feature on the left side.
 - Stitch Contour**: A label pointing to a dashed line indicating a weld path.
 - Weld 12**: A label pointing to a specific weld joint.
 - Weld 13**: A label pointing to another weld joint.
 - Weld 14**: A label pointing to a third weld joint.
 - Weld 15**: A label pointing to a fourth weld joint.
 - Weld 16**: A label pointing to a fifth weld joint.
 - Weld 17**: A label pointing to a sixth weld joint.
 - Weld 18**: A label pointing to a seventh weld joint.
 - Weld 19**: A label pointing to an eighth weld joint.
 - Weld 20**: A label pointing to a ninth weld joint.
 - Weld 21**: A label pointing to a tenth weld joint.
 - Weld 22**: A label pointing to an eleventh weld joint.
 - Weld 23**: A label pointing to a twelfth weld joint.
 - Weld 24**: A label pointing to a thirteenth weld joint.
 - Weld 25**: A label pointing to a fourteenth weld joint.
 - Weld 26**: A label pointing to a fifteenth weld joint.
 - Weld 27**: A label pointing to a sixteenth weld joint.
 - Weld 28**: A label pointing to a seventeenth weld joint.
 - Weld 29**: A label pointing to an eighteenth weld joint.
 - Weld 30**: A label pointing to a nineteenth weld joint.
 - Weld 31**: A label pointing to a twentieth weld joint.
 - Weld 32**: A label pointing to a twenty-first weld joint.
 - Weld 33**: A label pointing to a twenty-second weld joint.
 - Weld 34**: A label pointing to a twenty-third weld joint.
 - Weld 35**: A label pointing to a twenty-fourth weld joint.
 - Weld 36**: A label pointing to a twenty-fifth weld joint.
 - Weld 37**: A label pointing to a twenty-sixth weld joint.
 - Weld 38**: A label pointing to a twenty-seventh weld joint.
 - Weld 39**: A label pointing to a twenty-eighth weld joint.
 - Weld 40**: A label pointing to a twenty-ninth weld joint.
 - Weld 41**: A label pointing to a thirtieth weld joint.
 - Weld 42**: A label pointing to a thirty-first weld joint.
 - Weld 43**: A label pointing to a thirty-second weld joint.
 - Weld 44**: A label pointing to a thirty-third weld joint.
 - Weld 45**: A label pointing to a thirty-fourth weld joint.
 - Weld 46**: A label pointing to a thirty-fifth weld joint.
 - Weld 47**: A label pointing to a thirty-sixth weld joint.
 - Weld 48**: A label pointing to a thirty-seventh weld joint.
 - Weld 49**: A label pointing to a thirty-eighth weld joint.
 - Weld 50**: A label pointing to a thirty-ninth weld joint.
 - Weld 51**: A label pointing to a fortieth weld joint.
 - Weld 52**: A label pointing to a forty-first weld joint.
 - Weld 53**: A label pointing to a forty-second weld joint.
 - Weld 54**: A label pointing to a forty-third weld joint.
 - Weld 55**: A label pointing to a forty-fourth weld joint.
 - Weld 56**: A label pointing to a forty-fifth weld joint.
 - Weld 57**: A label pointing to a forty-sixth weld joint.
 - Weld 58**: A label pointing to a forty-seventh weld joint.
 - Weld 59**: A label pointing to a forty-eighth weld joint.
 - Weld 60**: A label pointing to a forty-ninth weld joint.
 - Weld 61**: A label pointing to a fiftieth weld joint.
 - Weld 62**: A label pointing to a fifty-first weld joint.
 - Weld 63**: A label pointing to a fifty-second weld joint.
 - Weld 64**: A label pointing to a fifty-third weld joint.
 - Weld 65**: A label pointing to a fifty-fourth weld joint.
 - Weld 66**: A label pointing to a fifty-fifth weld joint.
 - Weld 67**: A label pointing to a fifty-sixth weld joint.
 - Weld 68**: A label pointing to a fifty-seventh weld joint.
 - Weld 69**: A label pointing to a fifty-eighth weld joint.
 - Weld 70**: A label pointing to a fifty-ninth weld joint.
 - Weld 71**: A label pointing to a sixtieth weld joint.
 - Weld 72**: A label pointing to a sixty-first weld joint.
 - Weld 73**: A label pointing to a sixty-second weld joint.
 - Weld 74**: A label pointing to a sixty-third weld joint.
 - Weld 75**: A label pointing to a sixty-fourth weld joint.
 - Weld 76**: A label pointing to a sixty-fifth weld joint.
 - Weld 77**: A label pointing to a sixty-sixth weld joint.
 - Weld 78**: A label pointing to a sixty-seventh weld joint.
 - Weld 79**: A label pointing to a sixty-eighth weld joint.
 - Weld 80**: A label pointing to a sixty-ninth weld joint.
 - Weld 81**: A label pointing to a seventieth weld joint.
 - Weld 82**: A label pointing to a seventy-first weld joint.
 - Weld 83**: A label pointing to a seventy-second weld joint.
 - Weld 84**: A label pointing to a seventy-third weld joint.
 - Weld 85**: A label pointing to a seventy-fourth weld joint.
 - Weld 86**: A label pointing to a seventy-fifth weld joint.
 - Weld 87**: A label pointing to a seventy-sixth weld joint.
 - Weld 88**: A label pointing to a seventy-seventh weld joint.
 - Weld 89**: A label pointing to a seventy-eighth weld joint.
 - Weld 90**: A label pointing to a seventy-ninth weld joint.
 - Weld 91**: A label pointing to an eighty weld joint.
 - Weld 92**: A label pointing to an eighty-first weld joint.
 - Weld 93**: A label pointing to an eighty-second weld joint.
 - Weld 94**: A label pointing to an eighty-third weld joint.
 - Weld 95**: A label pointing to an eighty-fourth weld joint.
 - Weld 96**: A label pointing to an eighty-fifth weld joint.
 - Weld 97**: A label pointing to an eighty-sixth weld joint.
 - Weld 98**: A label pointing to an eighty-seventh weld joint.
 - Weld 99**: A label pointing to an eighty-eighth weld joint.
 - Weld 100**: A label pointing to an eighty-ninth weld joint.
 - Weld 101**: A label pointing to a ninety weld joint.
 - Weld 102**: A label pointing to a ninety-first weld joint.
 - Weld 103**: A label pointing to a ninety-second weld joint.
 - Weld 104**: A label pointing to a ninety-third weld joint.
 - Weld 105**: A label pointing to a ninety-fourth weld joint.
 - Weld 106**: A label pointing to a ninety-fifth weld joint.
 - Weld 107**: A label pointing to a ninety-sixth weld joint.
 - Weld 108**: A label pointing to a ninety-seventh weld joint.
 - Weld 109**: A label pointing to a ninety-eighth weld joint.
 - Weld 110**: A label pointing to a ninety-ninth weld joint.
 - Weld 111**: A label pointing to a hundred weld joint.



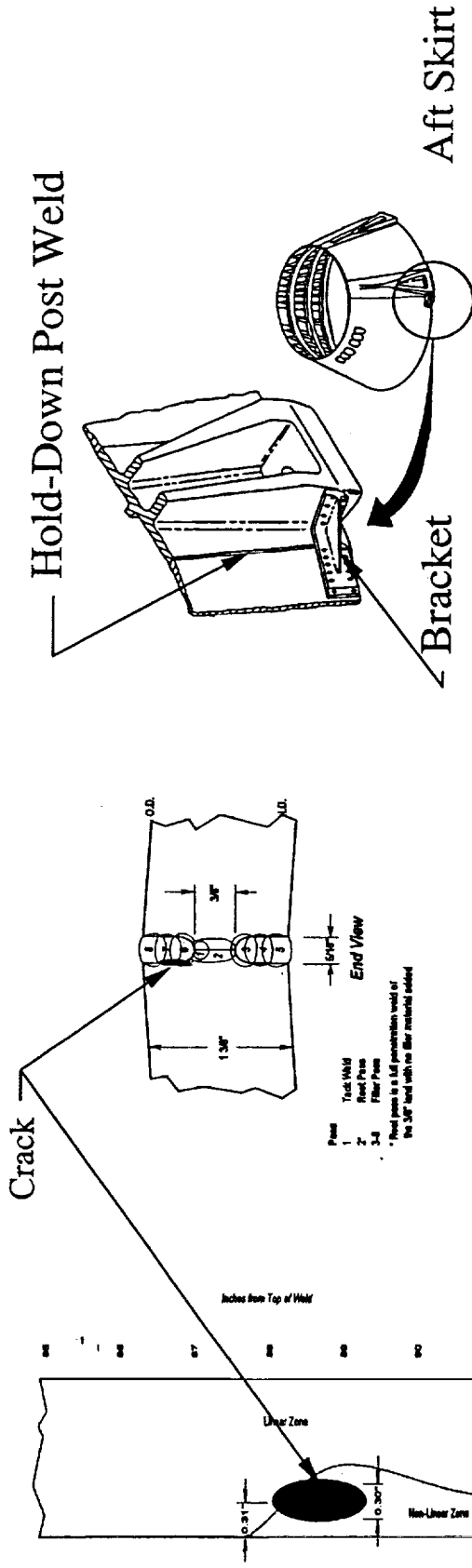
SSME Large Throat Main Combustion Chamber



Historical Example of Advanced LCF Analysis Need: Solid Rocket Booster

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- SRB Aft Skirt Hold-Down Post
- Nondestructive evaluation of weld indicated embedded defect near the edge of the critical weld at the hold-down post.
- Launch stresses in vicinity of defect exceed the tensile yield stress of the material.
- Abort event cyclic stresses exceed tensile yield and compressive yield.
- LEFM analysis not valid in region of defects.
- Stiffener bracket added to reduce stresses in weld to a point where LEFM could be applied for safe-life analysis.
- Verified tool for LCF crack growth analysis would likely have predicted adequate life and precluded the need for the stiffener bracket



Weld Sections



Project Technical Goals

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Provide MSFC and the Agency with an Advanced Modeling and Simulation Capability for LCF Assessments of Fracture Critical Components

- Adopt SwRI and Rocketdyne framework as starting point for all new work
 - Builds on advanced fracture methodology work sponsored by MSFC
 - Extend applicability/validity of ΔJ_{eff} approach through advanced micro-mechanical models & fracture concepts
 - Implement LCF simulation capabilities into the highly parallel, WARP3D Code
 - Improve usability aspects of WARP3D for LCF assessments of complex, 3-dimensional geometries & loading histories
 - Maintain the momentum in WARP3D development and improve collaborative research across NASA Centers and academia



Technical Approach

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ΔJ_{eff} Approach for LCF Assessments

- Simulations of cyclic, thermo-mechanical loading of complex, 3-D components containing cracks
- ΔJ Solutions extracted from 3-D simulations
- Direct computation of closure levels ($\Delta J \rightarrow \Delta J_{eff}$) in the 3-D models
- Transferability of model parameters, $da/dN(\Delta J_{eff})$, from lab tests to actual components (SSY \rightarrow LSY to include strong constraint effects)
- Environmental effects on da/dN

Addresses specific recommendations for new work in
SwRI & Rocketdyne studies



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$\Delta J_{SSY} - \Delta J_{LSY}$ Correlation

- Use micro-mechanical models that describe da/dN in terms of cyclic, crack front σ - ε fields, $da/dN = \Phi(\sigma, \varepsilon, \text{material props}, \dots)$
 - Some early fundamentals expected to be supported by the “Design for Safety” program out of ARC. Consortium approach - MSFC MP&M involved
- Use finite element analyses to couple ΔJ_{SSY} and ΔJ_{LSY} values which generate same $\Phi()$
 - Area of research with heaviest MSFC technical involvement
- Initial work to use $\Phi = \Phi(\Delta W_p + \Delta W_e)^*$ From D. Nelson’s most recent work* for multi-axial LCF (Including In 718)
- Environmental effects increase Φ (e.g. Hydrogen)
- This procedure extends the successful approach developed by Dodds, *et al.* to model constraint effects on fracture

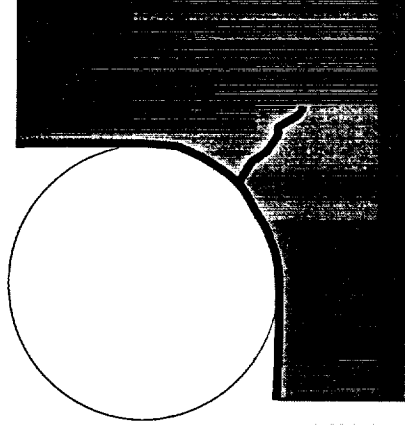
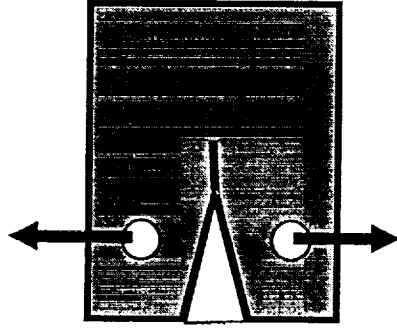
*Park, J., & Nelson, D. Evaluation of an Energy-Based Approach and a Critical Plane Approach for Predicting Constant Amplitude Multiaxial Fatigue Life. To Appear in *Int. J. Fatigue*, 2000.



Technical Approach WARP3D

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Key Issue: LSY-SSY Transferability



$$\left(\frac{da}{dN} \right)_{test} = C(\Delta J_{eff})^m$$

$$\left(\frac{da}{dN} \right)_{component} = C(\Delta J_{eff})^m$$

But, tests show: $\left(\frac{da}{dN} \right)_{test} \neq \left(\frac{da}{dN} \right)_{component}$

Because ΔJ_{eff} does Not generate same near-front stress-strain fields in the two conditions

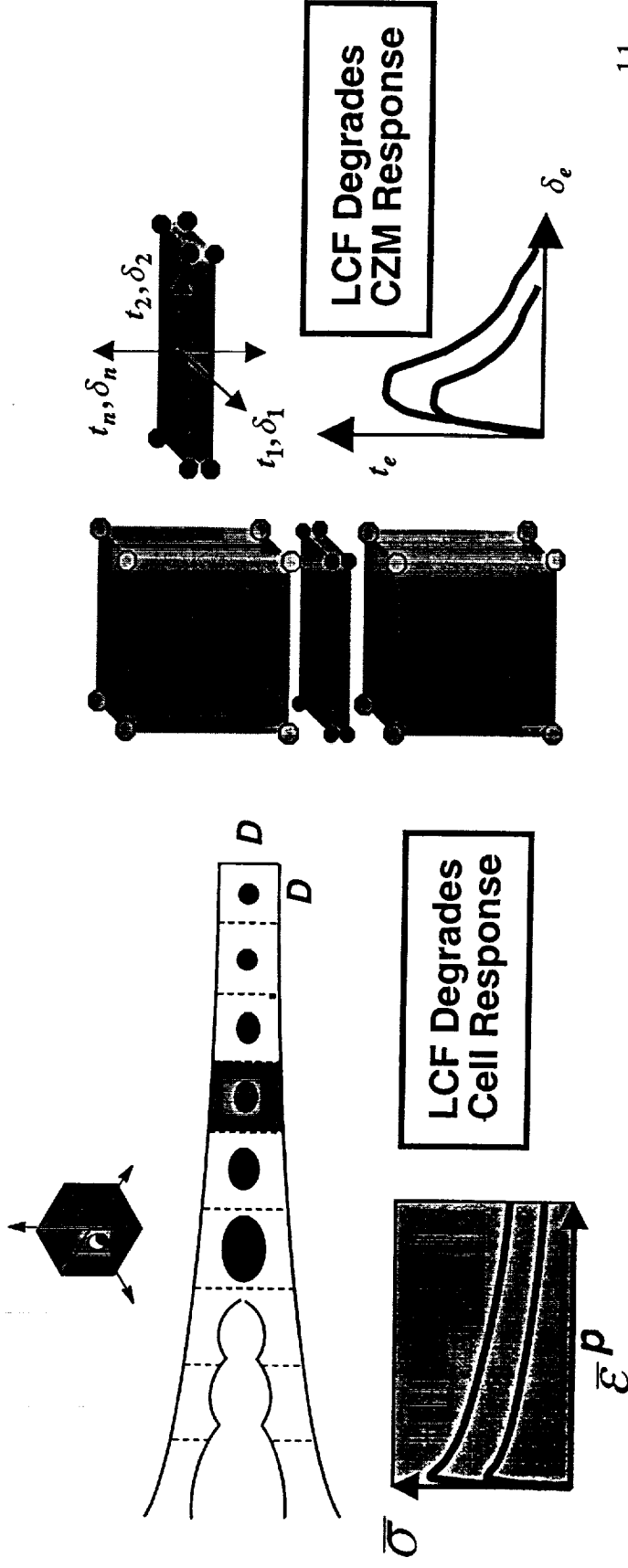


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Advanced Work Under Consideration

- Growing Cracks Due to LCF in Full 3-D Analyses
- Modify Cohesive Zone Models to Degrade Cohesive Properties Due to LCF Induced Material Damage
- Extend Cell Methodology to Incorporate a Failure Criteria Based on LCF Induced Material Damage





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New WARP3D Capabilities for LCF

- New Cyclic Plasticity Models, ΔJ , and 3-D Contact
- Usability Enhancements
 - Improved interface to specialized crack model generators
 - Improved interface to-from Patran and WARP3D
 - Automatic solution procedures to drive execution of LCF analyses
- Library of Standard 3-D Models for LCF Studies
 - Lab test specimens: SE(B), C(T)
 - Common 3-D geometries (e.g. surface cracks plates, pipes, elbows)



Participants

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- NASA-MSFC
 - Doug Wells / ED33*
 - Wayne Gregg / ED22*
 - Preston McGill / ED33*
 - Greg Swanson / ED22*‡
 - Ken Swaim / ED22*
- University of Illinois (UIUC)
 - Prof. Bob Dodds
 - Prof. Keith Hjelmstad
 - Prof. Petros Sofronis
 - Post-Doc Researchers
 - PhD Students
- NASA-AMES
 - Roy Hampton‡
- NASA-Langley
 - Jim Newman‡
- NASA-JSC
 - Royce Forman‡
- Stanford University
 - Prof. Drew Nelson (Project Consultant)
- SwRI Collaborative Efforts (NASGRO)
 - R. Craig McClung
 - Graham Chell
 - Yi - Der Lee

* MSFC Fracture Control Board

‡ NASA Fracture Control Methodology Panel



Participants & Roles

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MSFC: Project direction: Engineering Directorate lead with MSFC Fracture Control Board participation -- a new MSFC FCB activity

- Maintain focus on Center needs, material testing and FE analysis supporting code development and verification

ARC: Project advising

- Roy Hampton- NASA Fracture Control Methodology Panel, Primary NASA technical advisor to WARP3D development over past 4 years

LaRC: Project consulting

- Jim C. Newman- Recognized as the Agency-wide expert in fracture mechanics
- UIUC: Project theoretical development and coding

- Prof. Bob Dodds, Civil Engineering- Leader of WARP3D Development, Editor: *Engineering Fracture Mechanics*, recognized authority in computational fracture mechanics

- Prof. Keith Hjelmstad, Civil Engineering- expertise in cyclic plasticity and parameter estimation

- Prof. Petros Sofronis, Theoretical and Applied Mechanics- expertise in continuum models of hydrogen effects on metals

Stanford: Project consulting

- Prof. Drew Nelson, Mechanical Engineering- expertise in modeling and prediction of low cycle and multi-axial fatigue



Participants & Roles WARP3D Development

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Research Team Collaboration

- Technical Interchange Meetings for entire research team
- Regular Visits from UIUC at MSFC for Collaborations, Technical and Training Seminars
- Exchange Visits from UIUC of 2-3 Days During Academic Year
 - NASA people should visit UIUC as well
- Extended Summer Visits at NASA centers by Faculty, Post-Doc and PhD Students
- Updating & Direct Support for Development Versions of WARP3D Code, Mesh Generators on NASA Computers
- Assistance in Use of WARP3D and Mesh Generators to Perform LCF and Other Fracture Simulations